Incorporation of Quantum Statistical Features in Molecular Dynamics and Its Application to Heavy-Ion Collisions

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Currently, understanding of multifragmentation of hot nuclei has become one of the most important problems in heavy-ion physics both in the experimental and the theoretical side. It has been considered to be the result of the liquid-gas phase transition of nuclear matter, since nuclear matter behaves like a Van der Waals gas. When we study these multifragmentation events by the use of molecular dynamics, however, we confront the following difficulty: The quantal behavior at low temperature like $E^* \propto T^2$, which reminds us of the liquid-phase behavior, does not appear in these models, since the spectral distribution of energy eigen values are neglected in usual molecular dynamics [1].

Recently we have formulated a method for incorporating quantum fluctuations into molecular-dynamics simulations of many-body systems, by including the effects of the energy spread of each wave packet [2]. In the case of equilibrated system with the temperature $T = 1/\beta$, this energy spread affects the statistical weight of each wave packet $|Z\rangle$;

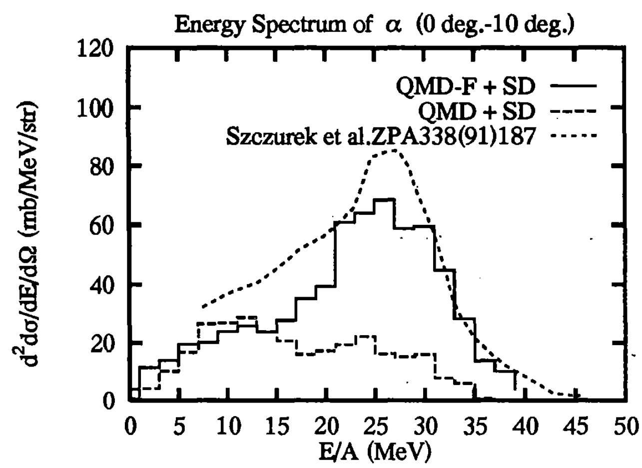
$$\mathcal{W}_Z \equiv \langle\, Z|\exp(-\beta\hat{H})|Z\,\rangle \approx \exp\left[-\frac{\mathcal{H}_Z}{D_Z}(1-\exp(-\beta D_Z))\right] \neq \exp\left[-\beta\mathcal{H}_Z\right] ,$$

where $\mathcal{H}_Z$ is the expectation value of the Hamiltonian, and $D_Z = \sigma_E^2/\mathcal{H}_Z$ represents the energy spread. This modification of statistical weight induces the Langevin force, which originates in the quantal fluctuation, in the context of dynamical evolution.

$$\left(\frac{d\boldsymbol{Z}}{dt}\right)_n^{Langevin} = -2\beta_Z\left(\boldsymbol{g}\cdot\boldsymbol{g}^\dagger\cdot\frac{\partial\mathcal{H}}{\partial\bar{\boldsymbol{Z}}}\right)_n + (\boldsymbol{g}\cdot\boldsymbol{\xi})_n ,$$

where $\boldsymbol{Z}$, β_Z, $\boldsymbol{g}$ and $\boldsymbol{\xi}$ represent complex phase-space parameters, the state-dependent inverse temperature, diffusion coefficients, and the white noise, respectively. By using this formulation, we can show that the ensuing diffusive evolution in the wave packet parameter space exhibits relaxation towards quantum-statistical equilibrium.

We have applied this model to the heavy-ion collision problem within the framework of Quantum Molecular Dynamics, and the calculated results show many appealing physical properties including the enhancement of intermediate mass fragments in the dynamical stage. They also show that the projectile-like fragment formation is also well described with this model. In the right figure, we show the energy spectra of α particle for ^{12}C (28.7 MeV/u)+^{12}C. We can see the enhancement of α particles at around the beam velocity when the quantal fluctuation is switched on (solid line), and the experimental data (dotted line)[3] is well reproduced.



[1] Akira Ohnishi and Jørgen Randrup, *Nucl. Phys.* **A565** (1993), 474.
[2] Akira Ohnishi and Jørgen Randrup, *Phys. Rev. Lett.* **75** (1995), 596.
[3] A. Szczurek et al.,, *Z. Phys.* **A338** (1991), 187.